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On an Air-to-Sea Guided Bomb

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Abstract

Even nowadays ships on the sea are important strategic base for aircraft and missiles. Thus we have been studying an unmanned attack system against ships recently. We experienced several problems when this system was simulated on the computer. In this paper, problems and solutions of an Air-to-Sea Guided Bomb for this system are presented

Nomenclature

h, x, y	: altitude, down range, cross range
X, Y, Z	: body fixed coordinates
ϕ, θ, ψ	: attitude angles(roll, pitch, yaw)
p, q, r	: rates about the axes
U_0, γ	: total velocity, path angle
U, V, W	: velocities along with the axes
F_x, F_y, F_z	: forces along with the axes
M_x, M_y, M_z	: moments about the axes
I_x, I_y, I_z	: moments of inertia
$\delta_a, \delta_e, \delta_r$	: aileron, elevator & rudder angles
L, D	: lift and drag forces
C_L, C_D	: lift and drag coefficients
$\alpha,\ \sigma$	: angle of attack, bank angle
t, β	: time, sideslip angle
T, t_h	: thrust, time const. for control surface
ρ	: air density
g	: acceleration of gravity
A_W, m	: wing area and mass
$_1$	: guided bomb # 1
$_2$	: guided bomb # 2
$_c$	: command values

1. Introduction

Even nowadays ships on the sea are important strategic base for aircraft and missiles. Thus we have been studying an unmanned attack system against ships recently. We experienced several problems when this system was simulated on the computer. In this paper, problems and solutions of an Air-to-Sea Guided Bomb for this system are presented.

From 40's up to date, the main option to eliminate the threat on the sea is an assault by aircraft with bombs and missiles, which is dangerous and costs high. Aircraft are surely expensive and rather more money and time is spent on training of pilots. And, even in the training, certain percentage of pilots will be lost.

Recently several long range anti-ship missiles are developed. They took advantage of modern electronic technology and succeeded to some extent. However, as they are missiles, the expensive devices, such as inertial navigation system, will be lost whether the mission was accomplished or not. It means the budget is high to establish and run the defense system with these missiles. Even against ships, this is a problem after the cold war.

In these years we have been studying Anti-Ship MLV System, an automatic ship attack system, which is consist of reusable unmanned aircraft called Maneuverable Launching Vehicle(MLV) and guided bombs. In this case, as MLV returns after the bombing, they are reusable. The only expendable parts are the guided bombs. Thus this system is economic through the operation and the exercises. It does not require pilots, either. So we need not worry about the casualties. Since MLV is an automatic attacker, it is not necessary to practice so many times. Then it is economic and safe at this point, too.

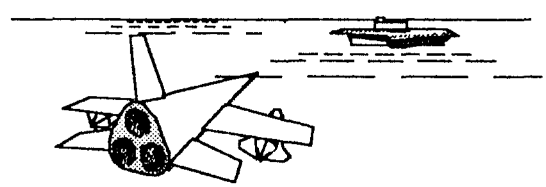

Fig. 1 Anti-Ship MLV System

The outline of the attack by the MLV System is the following. The MLV with two guided bombs are launched from ships, airplanes or vehicles on the shore. The unmanned aircraft flies as low as possible for the survivability. This low level flight and the toss bombing described below is not so easy for men and that was one of the reasons we chose automatic aircraft. First it was planned to fly to the attack entry point at the beginning of this study, which is located 10km behind the target, as missiles and bombs usually hit easily from the back of the moving target. But later it flies to the ship directly with the proportional navigation, as it turned out that there is no difference either from the back or from the front because the ship moves quite slow(36km/h). In either way, the MLV keeps on approaching until it reaches at 8km point from the ship. Then it pulls up and releases two guided bombs one after another, which is the toss bombing. At this point, MLV would be found. Therefore the toss bombing is a good way to avoid CIWS and to survive.

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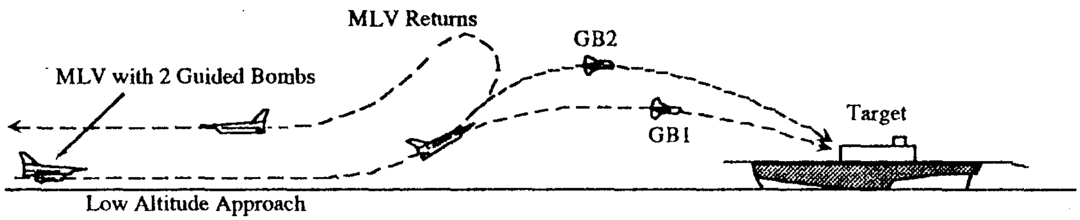


Fig. 2 Concept of the Attack System

Right after the bombing, the MLV starts evasive turn and returns. The guided bombs fly just on the parabolic trajectory until the middle. They start seeking the ship after the peak, begin the proportional navigation(PN) and pursuit the target. The MLV returns to the specified point and lands for itself.[2]

We simulated this system on a computer. We experienced several problems. In this paper, problems and solutions of an Air-to-Sea Guided Bomb for this system are presented.

2. Formulation

2.1 The Equations of Motion for the MLV

The equations of motion are expressed in 3-D Cartesian coordinates and the body fixed coordinates (shown in Fig. 3). The MLV is considered as a rigid body.

$$
\left.
\begin{aligned}
\frac{dx}{dt} &= U\cos\theta\cos\psi + V(\sin\phi\sin\theta\cos\psi - \cos\phi \\
&\quad \times \sin\psi) + W(\cos\phi\sin\theta\sin\psi + \sin\phi\sin\psi) \\
\frac{dy}{dt} &= U\cos\theta\sin\psi + V(\sin\phi\sin\theta\sin\psi + \cos\phi \\
&\quad \times \cos\psi) + W(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \\
\frac{dz}{dt} &= -U\sin\theta + V\sin\phi\cos\theta + W\cos\phi\cos\theta \\
\frac{dU}{dt} &= \frac{T-D}{m} - g\sin\gamma - qW + rV \\
\frac{dV}{dt} &= \frac{F_y}{m} + g\cos\gamma\sin\phi - rU + pW \\
\frac{dW}{dt} &= -\frac{L}{m} + g\cos\gamma\cos\phi - pV + qU \\
\frac{d\phi}{dt} &= p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\
\frac{d\theta}{dt} &= q\cos\phi - r\sin\phi \\
\frac{d\psi}{dt} &= q\sin\phi\sec\theta + r\cos\phi\sec\theta \\
\frac{dp}{dt} &= \left\{q_v b\left(B_p + C_{l\delta a}\delta_a + C_{l\delta r}\delta_r\right) + qr\left(I_y - I_z\right)\right\}/I_x \\
\frac{dq}{dt} &= \left\{q_v \bar{c}\left(B_q + C_{M\delta e}\delta_e\right) + pr\left(I_z - I_x\right)\right\}/I_y \\
\frac{dr}{dt} &= \left\{q_v b\left(B_r + C_{N\delta a}\delta_a + C_{N\delta r}\delta_r\right) + pq\left(I_x - I_y\right)\right\}/I_z \\
\frac{d\delta_a}{dt} &= (\delta_{ac} - \delta_a)/t_h \\
\frac{d\delta_e}{dt} &= (\delta_{ec} - \delta_e)/t_h \\
\frac{d\delta_r}{dt} &= (\delta_{rc} - \delta_r)/t_h
\end{aligned}
\right\} \quad (1)
$$

The controls are angles of aileron, elevator and rudder($\delta_{ac}, \delta_{ec}, \delta_{rc}$).

$$B_p = C_{l\beta}\beta + \frac{b}{U_0}\left(C_{lp}p + C_{lr}r\right) \quad (2)$$

$$B_q = C_{M0} + \frac{\bar{c}}{U_0}C_{Mq}q \quad (3)$$

$$B_r = C_{N\beta}\beta + \frac{b}{U_0}\left(C_{Np}p + C_{Nr}r\right) \quad (4)$$

$$q_v = \frac{1}{2}\rho U_0^2 A_W \quad \text{: Dynamic Pressure} \quad (5)$$

where

$C_{l\beta} = -0.04$, $C_{lp} = -0.3$, $C_{lr} = 0.12$, $C_{l\delta a} = 0.2$,
$C_{l\delta r} = 0.02$, $C_{M0} = 0.05$, $C_{M\alpha} = -0.1$, $C_{Mq} = -10.$,
$C_{M\delta e} = -0.8$, $C_{N\beta} = 0.11$, $C_{Np} = -0.04$,
$C_{Nr} = -0.26$, $C_{N\delta a} = -0.01$, $C_{N\delta r} = -0.1$

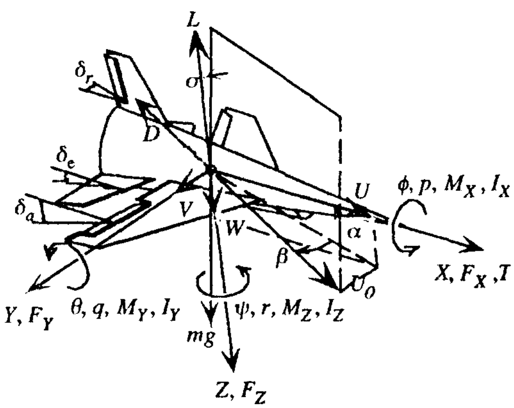


Fig. 3 Coordinate for MLV

Where C_L and C_D are functions of α.

$$C_L(\alpha) = 3.0\alpha \quad (6)$$

$$C_D(\alpha) = 0.018 + 3.0\alpha^2 \quad (7)$$

$$F_Y = q_v \times C_Y, \quad C_Y(\beta) = -0.7\beta \quad (8)$$

Note that $A_W = 6.8m^2$, m = 2800kg, $\bar{c} = 1.8m$ and $b = 5.4m$. The propulsion system is characterized by

$$T_{max} = 18130\text{N}, \; SFC = 9.1\times 10^{-5}/\text{sec} \quad (9)$$

The vehicle model is based on the Vehicle(MLV) studied in Ref. 4.

2.2 The Equations of Motion for the Guided Bombs

The equations of motion for the guided bombs are basically the same as the ones for the MLV. They are 3-

D Cartesian coordinates and the body fixed coordinates (see Fig. 4). The bombs are considered as rigid bodies. The roll motion is stabilized. The controls are the elevator and the rudder. As it is cylindrically symmetric, $I_Z = I_y$, $C_{Y\beta} = C_{L\alpha}$ and so on.

$$\left.\begin{aligned}
\frac{dx}{dt} &= U\cos\theta\cos\psi + V(\sin\phi\sin\theta\cos\psi - \cos\phi \\
&\quad \times \sin\psi) + W(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \\
\frac{dy}{dt} &= U\cos\theta\sin\psi + V(\sin\phi\sin\theta\sin\psi + \cos\phi \\
&\quad \times \cos\psi) + W(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \\
\frac{dz}{dt} &= U\sin\theta + V\sin\phi\cos\theta + W\cos\phi\cos\theta \\
\frac{dU}{dt} &= \frac{q_v C_{D0B}}{m} - g\sin\theta - qW + rV \\
\frac{dV}{dt} &= -\frac{q_v(C_{L\alpha B}\beta + C_{L\delta r}\delta_r)}{m} + g\cos\theta\sin\phi - rU \\
\frac{dW}{dt} &= -\frac{q_v(C_{L\alpha B}\alpha + C_{L\delta e}\delta_e)}{m} + g\cos\theta\cos\phi - qU \\
\frac{d\phi}{dt} &= q\sin\phi\tan\theta + r\cos\phi\tan\theta \\
\frac{d\theta}{dt} &= q\cos\phi - r\sin\phi \\
\frac{d\phi}{dt} &= q\sin\phi\sec\theta + r\cos\phi\sec\theta \\
\frac{dp}{dt} &= 0 \\
\frac{dq}{dt} &= q_v b_B\left(C_{M\alpha B}\alpha + C_{M\delta e}\delta_e + 0.5 b_B C_{Mq} q/U_0\right)/I_y \\
\frac{dq}{dt} &= q_v b_B\left(-C_{M\alpha B}\beta + C_{M\delta r}\delta_r + 0.5 b_B C_{Mq} r/U_0\right)/I_y \\
\frac{d\delta_e}{dt} &= \left(\delta_{ecB} - \delta_e\right)/t_h \\
\frac{d\delta_r}{dt} &= \left(\delta_{rcB} - \delta_r\right)/t_h
\end{aligned}\right\} \qquad (10)$$

where

$C_{D0B} = 0.17,\ C_{L\alpha} = 9.0,\ C_{L\delta e} = 6.0,$

$C_{M\alpha} = -0.4,\ C_{Mq} = -2.8,\ C_{M\delta e} = -2.5$

The target ship does not evade. It just runs straight at 36km/h. We do not believe it matters if the ship turned, because it is much slower than the bomb.

2.3 The Proportional Navigation for the Guided Bombs

The elevator angle and the rudder angle are calculated from the proportional navigation. The procedure is the following.

$$\vec{\sigma} = -\vec{U}_B \times \left(\vec{R}_T - \vec{R}_B\right)/\left|\vec{R}_T - \vec{R}_B\right| \qquad (11)$$

$$\vec{\sigma}_{\text{Body}} = E\vec{\sigma} \qquad (12)$$

$$\delta_{ecB} = \left(\vec{\sigma}_y\right)_{\text{Body}},\ \delta_{rcB} = \left(\vec{\sigma}_z\right)_{\text{Body}} \qquad (13)$$

E is the coordinate transformation matrix from the Cartesian inertial coordinates to the body coordinates, which is

$$E = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{bmatrix} \qquad \cdots\cdots(14)$$

We simulated this system on a computer, HITAC 680. The program was coded in FORTRAN77 and it has 1000 lines. We used 4th order Runge-Kutta method in a library for the integration of the equations of motions and it takes about 1 min. CPU time for each flight with 300000 steps integration.

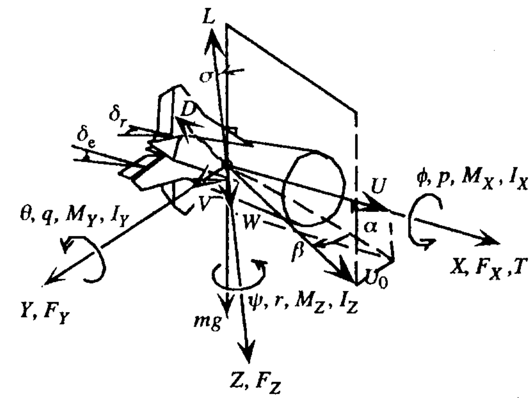


Fig. 4 Coordinates for the Guided Bombs

3. Results

Generally speaking, the Anti-Ship MLV System is possible, effective and economic. Most technologies of the cruising missiles are available to develop the MLV, the navigation system, the light weighted turbofan engine, launcher, booster and so on. The guided bombs already exist. When we simulated it on a computer, we found several problems of the guided bombs, but it was possible to overcome them.

Some of the results from the overall simulation is shown in Fig. 5 and Fig. 6. For a while after the boost phase, the MLV flies to the pre-specified point using INS. When it arrived near the position, it starts searching. If it acquires the ship, at this time the simulation begins, it starts the homing phase by the proportional navigation. Going close enough to the ship, the unmanned aircraft pops up, throws down the bombs and evades the lines of fire. The bombs initiate the proportional navigation after the peak of the parabolic trajectory and pursuits the ship.

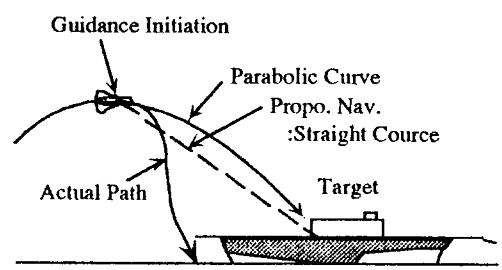
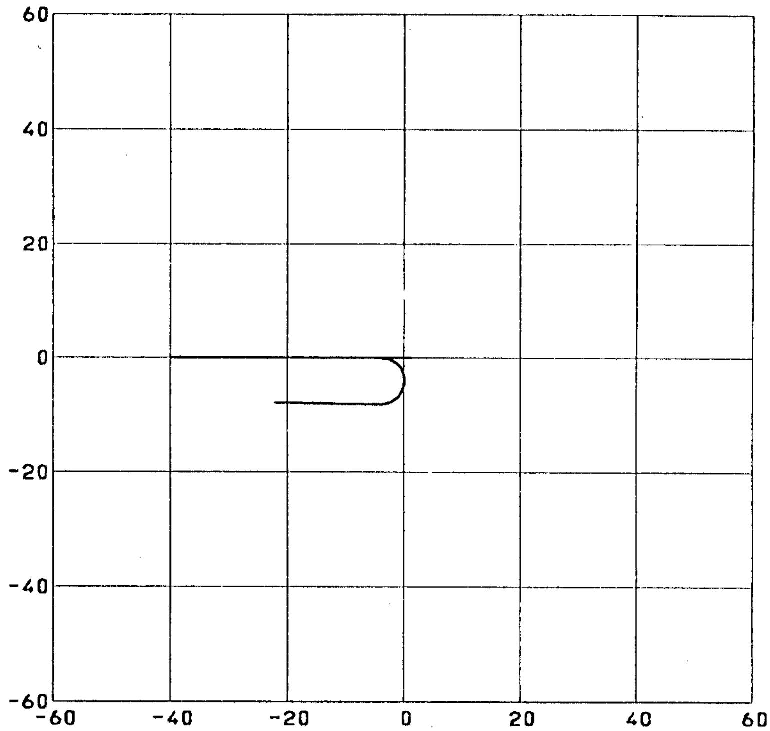
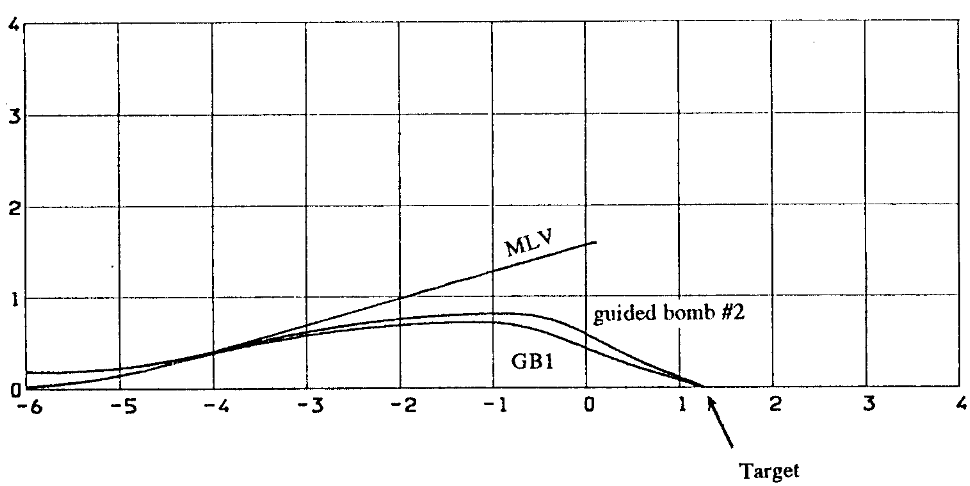


Fig. 7 The Problem of Undershooting

At first in this simulation, after minor troubles, we experienced some failures in the bomb guidance. First, several bombs fell before the target. It was because of the

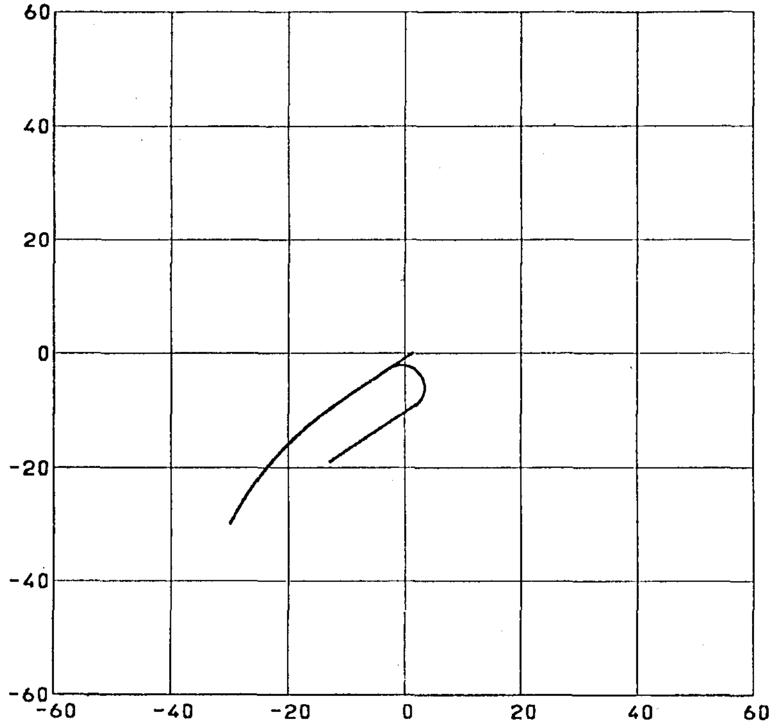


a) Plane View of the Trajectory of the MLV

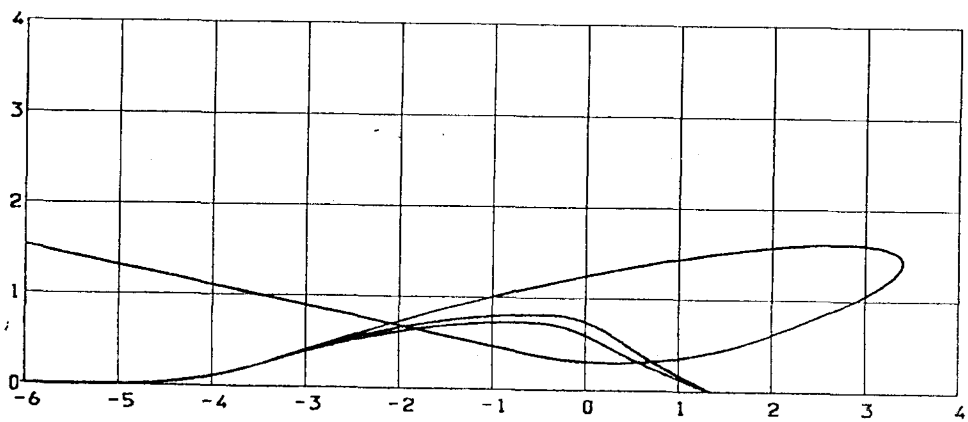


b) Side View near the target

Fig. 5 Simulation result 1



a) Plane View of the Trajectory of the MLV



b) Side View near the target

Fig. 6 Simulation result 2

proportional navigation. The guidance began after the peak of the toss bombing. The proportional navigation demanded straight flight to the target, though the bomb was on the parabolic curve and the gravity would correct the course of itself to some extent. As the result of the gravity and the control force, the bomb undershot unless there was enough room to recover(Fig. 7).

The solution for the first problem was that we set the algorithm to toss the bombs to overshoot the target (Fig. 8). Then the guided bomb traced deeper angle path than before after the initiation of the guidance. Consequently the normal component of the gravity reduced and the guided bombs come to hit the target every time.

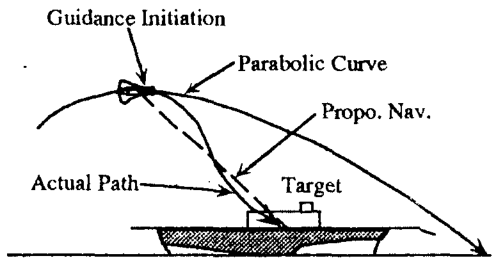


Fig. 8 The Solution with Overshooting Toss

But next problem was that we found the angle of attack of the bomb too large when we checked the simulation data(Fig. 9). Especially that of the second bomb, the guided bomb #2, was. The reason was that the proportional navigation tried to change the path angle largely and suddenly at the guidance initiation, since the projectile was overshot intentionally and the guidance law always demands a straight course to the target. The pitching angle of the second bomb changed more than the first one because it tossed higher. There had not been any limit for the angle of attack, but over 30 degree is obviously excessive.

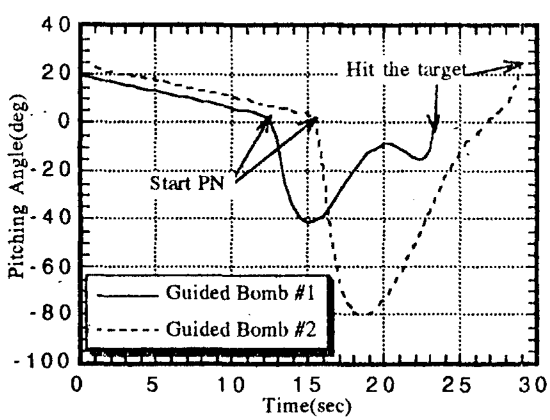


Fig. 9 Time History of Attitude of Guided Bombs

After all, these problems were caused from the shortage of the aerodynamic ability, namely the lift of the bomb. The troubleshoot for this was to enlarge the wing area and toss the bomb to undershoot the target (Fig. 10). Then after the peak, when the target is acquired by the seeker, the difference between the line of sight and the path angle is not so big and it need not change the attitude so suddenly. The MLV can release bombs farther from the ship in this case, which means it is safer for the MLV.

And later we are informed that the seeker would not have a large angle of view, about ± 20 degrees or less. Thus also from this reason, the undershot toss is preferable. Because, in this case, the target will come in sight soon after the peak(see Fig. 9) ; In the other cases much later or even never. It was not until that time that we realized this point of view.

Finally we simulated this system including bombs with various initial positions, and we verified that all the bombs hit the target from all the initial positions around the ship. Some of the simulation result can be seen in Fig. 5 and Fig. 6.

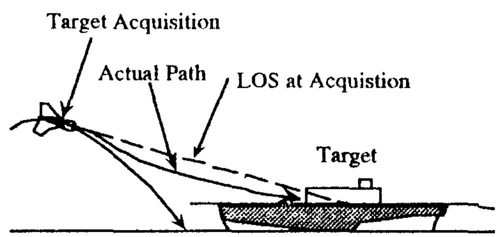


Fig. 10 Large Wing and Undershooting Toss

5. Conclusion

We have been studying an unmanned attack system against ships recently. We experienced several problems when this system was simulated on the computer. In this paper, problems and solutions of an Air-to-Sea Guided Bomb for this system are presented

Generally speaking, the Anti-Ship MLV System is possible, effective and economic. Fundamentally it is possible to develop the MLV. Most technologies of the cruising missiles are available, the navigation system, the light weighted turbofan engine, launcher, booster and so on. The guided bombs already exist. When we simulated it on a computer, we found several problems of the guided bombs, but it was possible to overcome them.

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